Met.O.854
METEOROLOGICAL OFFICE

the meteorological magazine

JANUARY 1972 No 1194 Vol 101
Her Majesty's Stationery Office

METEOROLOGICAL OFFICE Met.O.854

THE METEOROLOGICAL MAGAZINE

Vol. 101, No. 1194, January, 1972

551.510.42:551.551.8:628.53

FACTORS DETERMINING POLLUTION FROM LOCAL SOURCES IN INDUSTRIAL AND URBAN AREAS*

By F. PASQUILL

General role and action of the atmosphere. The discharge into the atmosphere of gases and small particles from combustion and chemical processes is the beginning of a complex series of actions. These may be considered in three main stages :

(a) general drift in the prevailing airstream with progressive spreading sideways and vertically,

(b) chemical and physical transformation in the airborne stage, and

(c) removal from the atmosphere by various natural processes.

All these stages are important to some degree in controlling the resultant level of pollutant concentration. For the local effects, i.e. those within a distance of say 10 kilometres from the source, the determining factor is more often (a), though (b) and (c) cannot be generally ignored and may sometimes be decisive.

The general drift in the airstream introduces a particularly effective and direct dilution of the pollutant when, as is usual, this is emitted gradually. Then the pollutant emitted over a given time will tend to be distributed through a volume of air directly proportional to the wind speed. In this respect wind speed is one of the most important meteorological factors.

Apart from the general transporting action and initial dilution the lower atmosphere also exerts a progressive diluting action, through the vertical and sideways spreading by the turbulent and convective motions which disturb an otherwise steady flow. In the same way material released in concentrated batches is spread alongwind as well as vertically and sideways.

The intensity of the turbulent variations in the wind is greater the rougher the underlying surface, and is markedly affected by the day-time heating or nocturnal cooling of the surface, vertical mixing being respectively enhanced or suppressed. The depth of the atmosphere over which rapid vertical mixing extends (the mixing depth or layer) depends on the temperature profile and is frequently limited decisively by an overhead stable layer in which there is an inversion.

* This paper was prepared as a contribution to the World Meteorological Organization documents for the forthcoming United Nations Conference on the Human Environment.

The velocity fluctuations which produce vertical spread are so rapid that in most cases their full action is achieved in 10 minutes or so, i.e. in so far as the concentration downwind of a continuous emission is dependent on vertical spread, the concentration will have reached a fairly steady value when exposure to the effluent has continued for such a period. However, those fluctuations (in wind direction) which affect sideways spread include very much slower variations in addition, extending over hours and days. Accordingly the reduction of average concentration by crosswind spreading continues progressively as the exposure time of interest (or sampling time) is extended into tens of minutes, hours, days and so on.

Theoretical treatments of dispersion. The literature available on the theoretical treatment of the effects of atmospheric turbulence in diluting windborne material is now very extensive.[1,2] All treatments demand idealization of the flow situation as a prerequisite for representing the dispersive action in a way that can be handled mathematically. Different degrees of sophistication are attempted in the various mathematical analyses but all the resulting dispersion formulae are necessarily of common form to the extent that the concentration downwind of a continuous emission is

(a) directly proportional to the rate of emission, and

(b) inversely proportional to the product of the wind speed, the crosswind spread and the vertical spread.

The product in (b) represents the effective volume of air over which a given amount of material has been spread and neglects effects of wind speed other than that of direct dilution. In this respect the theoretical treatments do no more than formalize relations expected on simple physical grounds, and their most important potential is in correctly representing the magnitudes of the spreads in relation to measurable meteorological properties.

The fact that the theoretical treatments refer to idealized conditions of flow and terrain, which are rarely realized in situations for which air pollution is a problem, is often quoted as a criticism of their inherent value. Moreover, such are the virtually random variations in the apparent dispersive behaviour of the natural atmosphere that at best the theoretical treatments offer estimates of *average* behaviour, from which the behaviour on individual occasions may be expected to depart to some extent. It is important to keep these reservations in mind, but there are many situations of weather and terrain and many types of practical questions for which it will be technically useful and economically worth while to be able to make estimates of likely pollutant concentration without embarking on difficult and prolonged measurements of actual pollutants or of tracers simulating them. In all cases it is preferable that the application of the theoretical treatments should be made by scientists with meteorological experience, who can also through that experience make as much allowance as possible for the particular nature of the site and terrain and for the non-ideal nature of the airflow.

Practical systems for estimating dispersion. In any practical system for estimating the dispersion of pollutants the aim must be to combine to the best advantage three components :

(a) the idealized theoretical treatments, reduced to a simple but flexible type of formula,

(b) the practical experience gained from tracer studies and previous air pollution surveys, and

(c) the specialized knowledge available or obtainable on the particular configuration of the emission site and the area downwind.

In addition to the information on wind velocity — and here of course the general direction is important in defining the zone affected — the main meteorological problem is that of appropriately representing the crosswind and vertical spreads. Full use of the available theoretical treatments requires meteorological measurements which except in special and limited projects are too detailed and specialized to be envisaged. Examples are the fine detail of the temperature profile near the ground and the magnitude and scale of the turbulent fluctuations. For general and extensive practical use the estimation has to proceed in terms of routine meteorological data.

Of the available routine data the factor most directly reflecting the amount of day-time surface heating or night-time cooling (hence the 'stability' in the lower atmosphere) is the amount of cloud. It is possible to define combinations of state of sky and wind speed to represent categories of stability and to assign to them 'normal' values of the spreads. A system on such lines[3] was designed in the Meteorological Office over 10 years ago and continues to be used widely. Rough but useful estimates of the effects of a given source on the level of pollution may thus be made given only the wind speed and direction and state of sky (with the locality, date and time otherwise determining the amount of sunshine). Such a system can be used in planning studies and also in operational studies in the absence of special meteorological data. Improvements in various aspects of the system may be expected as basic knowledge is increased and experience gained.[4] The accuracy achievable depends on how well the terrain and flow conditions conform to the ideal state and on the correctness of the meteorological data. On individual occasions the actual short-term concentration may differ one way or the other from that estimated, by a factor of several-fold.

Effect of elevation of sources. The significance of the usually gradual nature of pollutant emission as regards dilution has already been noted. The other very important characteristic of the source is its elevation above the general ground level. Elevation is advantageous as long as the plume of pollution is not deflected downwards as a whole. Then a definite amount of vertical spread (and a corresponding amount of crosswind spread) must occur before the edge of the plume reaches ground level. The more intense concentration of pollution close in to the source is thereby avoided at ground level, and the maximum concentration now occurs some distance away depending on the height of the source. Thereafter the concentration at ground level decreases, always being lower than that which would have occurred had the same source been at ground level, but tending closer and closer to this value as distance increases.

For a given elevation of source the distance at which the pollution appears at ground level with maximum effect depends on the rate of vertical spreading and hence on the stability of the atmosphere. Thus the effects of an elevated source may be apparent at very short range in unstable conditions. On the other hand in stable conditions it has been known for an elevated plume to travel tens of kilometres without the ground being affected.

Wind speed has an important effect on the behaviour of an elevated plume, in addition to the diluting effect, in that it controls the amount by which a hot plume may rise above the chimney exit and so determines the effective total height of the plume. A strong wind keeps the plume low, so that a relatively small amount of vertical spread is required for the ground to be affected, and so this effect of wind speed is in opposition to its direct diluting action. It is also likely that at the greater heights reached by modern power station plumes the relative magnitudes of the vertical and crosswind spreads are also affected by wind speed, but to an extent which is not yet clear. The overall influence of wind speed may thus be rather more complex then is assumed in the usual simple model treatment of an elevated source. However, recent surveys[5] suggest that except in a combination of light wind and unstable conditions the concentrations are on average somewhat less than those estimated from the simple model, in which the ratio of the spreads is taken to be a constant independent of wind speed and distance.

Multiple sources. Although there may be considerable interest in the effects of a single large source of pollution there is also an obvious and perhaps overriding interest in the combined effect of an array of various sources in an urban-residential area or an urban-industrial complex. There has accordingly been a focusing of interest recently on the methods of making estimates of concentration in such cases, from source inventories and meteorological or climatological data. This so-called 'mathematical modelling' of the effects of multiple sources is essentially a matter of summing individual contributions which in the simplest context are independent and directly additive.

The summation may be carried out in two ways :

(a) by a mathematical integration — which is possible for certain simplified forms of the dispersion formulae — leading to a convenient formula representing the overall effect in terms of the total output over a specified area, and

(b) by a numerical summation on a computer — the effects at any point being first evaluated separately for all sources or convenient combinations of small sources.

It should be emphasized however that both methods depend ultimately on the validity of the dispersion formulae, and on the quality of the data on source inventory, wind speed and direction, and spread.

Both methods have been tried, though recently the emphasis has been on the second.[6] Very extensive arithmetic is required but this can be carried out very quickly on modern high-speed computers. It is debatable however whether the realism of the final answers is always likely to be enough to justify the great elaboration advocated in the numerical models. There is some indication[7] that a combination of both methods may be advantageous in eliminating much of the numerical labour without seriously reducing the validity of the results. The advantage may be particularly significant when use is made of the principle that other things being equal the concentration at a given position will be dominated by the sources in a relatively small area immediately upwind.

It is to be expected on theoretical grounds, and is evident from practical surveys, that in a multiple-source situation concentrations vary widely from position to position in the area, and from time to time. Nevertheless, the

concentration averaged over a long time and over the whole of the multiple-source area may be predictable with some accuracy (within a factor of two, say). On the other hand, the concentration estimated for a particular position, even when averaged over some hours, may be very much more in error.[8] Thus although much of the point of method (b) lies in the prospect of correctly representing variability of the concentration in space and time this seems unlikely in respect of individual positions and periods. It is possible however that the application of the method to a large number of periods may provide a realistic estimate of the *range* of variation at a given position.[9]

Complexities of weather and terrain. It has already been emphasized that ideal conditions of flat uniform terrain and straightforward airflow are necessarily assumed in any simple generalizations about the local distribution of air pollution. In practice there are many departures from this ideal, the more important being as follows :

(a) *The effect of buildings.* In a collective sense these affect the general level of turbulence in the airflow, and some useful allowance for this may be estimated when the dispersion has proceeded sideways and vertically well beyond the sizes of individual buildings. The principal difficulty arises from the immediate local effect on a nearby source of the aerodynamic disturbance by an individual building. Only very crude generalizations can at present be offered, and the best hope for accumulation of necessary experience seems to lie in wind-tunnel work.[10]

(b) *Topographical effects.* Irregular terrain introduces important modification of the general drift of pollutants. Apart from the physical deflexion and channelling of the airflow there occur downslope (drainage) winds from cooling at night and upslope winds from heating during the day. Dispersion tends to be affected adversely mainly by the vertical confinement of the air in valleys in stable conditions and the direct prevention of cross-stream spreading by valley sides. Useful attempts have been made to allow for such effects in the adaptation of the methods applicable to flat terrain.

(c) *Light winds and calms.* These are the conditions which, especially in association with slow or restricted vertical mixing or with topographical confinement of the airflow, lead to the disastrous air pollution incidents. The slow drifting and dispersive action of the atmosphere is then not readily and reliably estimated by the usual procedures. Such extensions as are made of these procedures must be regarded with caution and even more reliance than usual placed on actual experience at particular sites in stagnant air situations.

Warning, forecasting, climatology. The ultimate basis for the preparation of warnings or forecasts of the incidence of important levels of air pollution is in the known relations between the concentration field, the source distribution and the meteorological conditions. In principle therefore a warning procedure may be designed in terms of continuous measurements of a significant meteorological parameter — such as the level of turbulence or the detailed form of the vertical profile of temperature — from which these relations may be evaluated. In the practice of warnings and forecasting, as in that of planning and operational studies of air pollution, the meteorological

requirements must generally be reduced to those normally satisfied in the regular programme of a national weather service. This means also that the parameters of the source/dispersion relation must be in terms of wind speed, broad vertical profile of temperature as available from routine upper air data, and state of sky.

The only general system[11] known to be in current and continuous operation is based on forecasting the expected occurrence and continuation of large areas of stagnant air, within which a build-up of pollution would be possible. Extension of this purely qualitative 'air pollution potential' forecasting is in hand in terms of a simple 'box' model in which the pollutant is assumed uniformly distributed over the 'mixing depth'. The product of this 'mixing depth' and the wind speed constitutes an effective dilution factor to be applied to the amount of pollutant released upwind of any position. An approximation to the 'mixing depth' is available from the routine upper air data by applying the same procedure as the weather forecaster uses for estimating the likely vertical extent of convection.

A further possible step in the development of pollution forecasting would be to use forecasts of wind speed and cloud cover, to derive a forecast 'stability category' which could be used in more detailed calculations of concentration. It would be important in any such further elaboration to keep in mind the very rough quality of the final answers. However, in practice the important requirement will often be the provision of warnings of the likely incidence of relatively intense pollution. In respect of sulphur dioxide pollution in urban areas it seems likely that useful rules may be formulated from an examination of available data on day-to-day variations in relation to wind speed, temperature and stability.[12]

The climatological statistics on wind speed, wind direction and cloud amount prepared from routine observations are immediately usable in any requirement for the estimation of long-term average concentration or of the frequency of incidence of specified levels of pollutant concentration. The procedure does of course need to be used with caution, not only because of the inevitably crude representation of the dispersive action of the atmosphere, but also because there may be correlations in the occurrence of the basic meteorological elements, e.g. cloud cover and wind direction, which are not evident from separate statistics of these properties.

There is now the possibility of deriving a more specialized climatology for such features as the mixing depth and stability categories, but so far such analyses have been on a very limited scale.

Transformation and natural removal of pollutants. The pollutants of major interest are neither chemically inert nor permanently retainable in the atmosphere and their dispersion after release is accompanied by a complex chain of chemical reactions[13] and physical removal processes.

One of the most important transformations is the solution and oxidation of sulphur dioxide to give sulphuric acid and sulphates. The solution may occur at free water surfaces, on wet ground and other solid surfaces, on vegetation, and in drops of fog, clouds and rain. The process is of immediate practical importance as regards corrosion of materials. If the oxidation is in the presence of ammonia, hygroscopic ammonium sulphate results and in aerosol form this has an important effect on visibility. Transport to ground

in rain or direct uptake at wet surfaces (including vegetation even in a nominally dry state) progressively depletes the atmosphere of the sulphur dioxide or secondary products. The relative amounts of sulphur dioxide deposited and remaining airborne depend on many factors: the initial elevation of the source, the dispersive conditions, the intensity of rain and the nature and wetness of the underlying surfaces. The complexity of the processes is reflected in the variability of the effective life-time of sulphur dioxide in the atmosphere — estimates range from an hour to several days[13-15] — and the significance of this to the concentration and effect of sulphur dioxide locally requires continuing study.

The other chain of processes which attracts great interest is that which leads to the 'photochemical smog' so well known in Los Angeles. Photochemical dissociation of nitrogen peroxide, which appears to be enhanced in the presence of certain hydrocarbons (including those in car exhausts), produces ozone, which in turn reacts with the hydrocarbons to form compounds with irritant properties. For these processes the favourable meteorological conditions are those of limited transport and dispersion in the presence of abundant sunshine, a combination occurring most effectively in anticyclonic conditions in relatively low latitudes, especially when there is topographical impedance to the large-scale airflow, as in the Los Angeles basin.

Future needs. Features which are considered to be in special need of further consideration are :

(a) The provision of improved low-level temperature soundings or of other measurements capable of prescribing the general 'mixing depth', and the extension of the climatology of 'mixing depth' and 'stability categories'.

(b) Standardization of the practical systems for estimating and forecasting the levels of air pollution from emission data and meteorological data, embodying improvements provided by recent researches but avoiding complexities which are not warranted by the expected quality of the final answers.

(c) Improvement of the understanding and representation of the chemical transformation and natural removal of air pollutants.

REFERENCES

1. PASQUILL, F.; Atmospheric diffusion. D. van Nostrand, London, 1962.
2. SLADE, D. H. (editor); Meteorology and atomic energy. Oak Ridge, Tennessee, United States Atomic Energy Commission, 1968.
3. PASQUILL, F.; The estimation of the dispersion of windborne information. *Met Mag, London*, **90**, 1961, pp. 33–49.
4. PASQUILL, F. and SMITH, F. B.; The physical and meteorological basis for the estimation of the dispersion of windborne material. Proceedings of the 2nd International Clean Air Congress, Washington, D.C., 1970, (in press).
5. London, Meteorological Office. A discussion on recent research in air pollution. *Phil Trans R Soc, London*, **265**, 1969, pp. 139–318.
6. North Carolina, Research Triangle Park, U.S. Environmental Protection Agency. Proceedings of symposium on multiple-source urban diffusion models, 1970.
7. GIFFORD, F. A. and HANNA, S. R.; Urban air pollution modelling. Proceedings of the 2nd International Clean Air Congress, Washington, D.C., 1970 (in press).
8. MARSH, K. J. and WITHERS, V. R.; An experimental study of the dispersion of the emissions from chimneys in Reading — III: the investigation of dispersion calculations. *Atmos Environ, Oxford*, **3**, 1969, pp. 281–302.
9. PASQUILL, F.; The prediction of diffusion over an urban area — current practice and future prospects.[6] 3-1-3-26.
10. HALITSKY, J.; Gas diffusion near buildings.[2] pp. 221–255.

11. MCCORMICK, R. A.; Meteorological aspects of air pollution in urban and industrial districts. *Tech Notes, Wld Met Org, Geneva*, No. 106, 1970.
12. SMITH, F. B. and JEFFREY, G. H.; The prediction of high concentrations of sulphur dioxide in London air. London, Meteorological Office, 1971 (in press, copy to be available in the Meteorological Office Library, Bracknell).
13. JUNGE, C. E.; Air chemistry and radioactivity. New York, Academic Press, 1963.
14. ROBINSON, G. D.; Long-term effects of air pollution — a survey. Hartford, Connecticut, The Center for the Environment and Man, Inc., 1970.
15. MEETHAM, A. R.; Atmospheric pollution, 3rd Edn. Pergamon Press, Oxford, 1964.

551.577.37:629.7

PROBABILITIES OF AIRCRAFT ENCOUNTERS WITH HEAVY RAIN

By J. BRIGGS

Summary. Estimates of probabilities of aircraft encounters with heavy rain have been obtained for three localities. The estimates are necessarily based on somewhat arbitrary assumptions, especially as regards the variation in rainfall probabilities with variation of height. However, the assumptions are reasonably supported by observational evidence and the method used has the merit that estimates can be made fairly readily for any area where the available rainfall data are adequate.

Introduction. The possibility of erosion of aircraft structures by rain becomes increasingly important as the operating speed of aircraft increases. Designers and airworthiness authorities require estimates of the chances that an aeroplane will meet rain that might cause structural damage or might lead to the wearing-away of materials.

This note presents some estimates of the probability that an aircraft will meet heavy rain. The estimates are based on available rainfall data and are limited to flight in the vicinity of a few stations but the method can be used for any place or route for which data are to hand. Since the problem of rain erosion is of great importance to supersonic aircraft the estimates have been based on the probable operating conditions for Concorde.

Method. Suppose that the probability of a particular rate of rainfall at a point on the ground is P_p whilst the corresponding probability of the same rainfall rate somewhere inside an area of unit radius is P_a. If the typical radius of a rain cell of the intensity being considered is R [where R is considerably less than unit radius] then

$$P_a \approx P_p/R^2.$$

Now assume that the rainfall probability is the same aloft as at the ground and that no avoiding action is taken, then the chance of an aircraft encounter with a rain cell during the crossing of an area of unit radius is

$$\frac{4P_aR}{\pi} \text{ or } \frac{4P_p}{\pi R}.$$

If the aircraft speed is V then the time taken to cross the area is $2/V$ and so the probability of an encounter with rain of the specified intensity in unit time is

$$\frac{4P_p}{\pi R}\,\frac{V}{2} = \frac{2P_pV}{\pi R}. \qquad \ldots (1)$$

Estimates of P_p. Much rainfall information is available for many stations though the data are often limited to daily or monthly rainfall totals whereas

the problem here relates to instantaneous rainfall rates. However, for an increasing number of places the use of recording rain-gauges has permitted hourly rainfall totals to be obtained and these totals can be used to determine the required probabilities of instantaneous rainfall intensities.

Briggs and Harker[1] have obtained typical distributions of two-minute rainfall rates about the clock-hour totals and have hence derived conversion factors which enable occurrence of instantaneous rates of rainfall to be assessed on the basis of available clock-hour data. Estimates of P_p thus obtained are presented in Table I for a limited number of stations and rainfall rates.

TABLE I—PROBABILITY OF OCCURRENCE OF INSTANTANEOUS RAINFALL AT OR EXCEEDING SPECIFIED INTENSITIES

	Rainfall intensity (mm/h)		
	25	50	100
		probability	
Heathrow	$1 \cdot 26 \times 10^{-4}$	$1 \cdot 94 \times 10^{-5}$	$1 \cdot 14 \times 10^{-6}$
Singapore	$1 \cdot 83 \times 10^{-3}$	$6 \cdot 85 \times 10^{-4}$	$1 \cdot 48 \times 10^{-4}$
Freetown	$3 \cdot 31 \times 10^{-3}$	$1 \cdot 26 \times 10^{-3}$	$3 \cdot 19 \times 10^{-4}$

Rain-cell diameters. The pattern of rainfall during the passage of a heavy shower can vary widely but in general each period of light or moderate rain will include a shorter period of heavier rain. On the average the shower profile will have a reasonably smooth intensity/time distribution and the higher the intensity considered the shorter will be the typical duration.

Durations of rainfall can be determined by inspection of the charts of recording rain-gauges and may then be combined with estimated speeds of movement of the rain-bearing clouds to give values for the rain-cell diameters. Table II presents estimates of typical rain-cell diameters obtained for the places listed in Table I.

TABLE II—AVERAGE CELL DIAMETER (km) FOR RAINFALL AT OR EXCEEDING SPECIFIED INTENSITIES

	Rainfall intensity (mm/h)		
	25	50	100
		kilometres	
Heathrow	3	2	1·5
Singapore	3·5	2·5	2
Freetown	4	3	2

As must be expected the typical diameter decreases as the intensity of the rainfall increases. The table also reflects the influence of the average temperatures of the places concerned — the amount of water vapour which is ultimately available for release as rain is temperature-dependent and so the average cell diameter increases as the temperature rises. The figures of Table II are also in good accord with the diameters suggested by radar studies of the cores of heavy showers.

Rain-cell diameters will vary with altitude but it will be assumed here that the diameter remains reasonably constant throughout the depth of a heavy shower.

Variation of the probability of rainfall occurrence with height. The rainfall rates of interest in the rain erosion problem are mainly those exceeding, say, 10 mm/h and such rates are normally limited to showery

conditions, though orographic intensification can cause such intensities inside widespread frontal-type rain. Radar studies, see, for example, Hamilton,[2] give some indication of the distribution of precipitation in the vertical. Although widespread rain usually shows a steady decrease of precipitation content with height increase it seems that the large precipitation densities occurring in the core of severe showers have a fairly uniform distribution throughout the bulk of the shower cloud.

The problem here is to determine how the probability of rainfall occurrence varies with height on the average, not just for one particular shower cloud. The probability at a given height will be compounded of the probability of a shower cloud top reaching to that height together with the probability of a given rainfall rate inside a shower cloud which extends to a given height.

Some indication of the probability of a given precipitation rate inside a shower cloud has been obtained by Donaldson[3] who measured radar reflectivities inside some 233 thunderstorms over New England. Radar reflectivity is essentially a measure of the water-substance contained in the larger raindrops, snow and hail but in interpreting the radar observations it is necessary to consider how the normal fall-off of temperature with height affects the rain/snow ratio. In many rainfall situations most of the large raindrops can be expected to have become frozen at heights above that corresponding to temperature of −20°C, i.e. above about 7 km for temperate climates and about 8 km for tropical climates. However, the heavy rain of main interest occurs in heavy showers or thunderstorms where strong updraughts rapidly distribute the water drops and so give good reason to ignore the freezing of the drops in the time available before cloud top is approached. Thus it is thought that Donaldson's profiles of radar reflectivity in thunderstorms give a good picture of the height distribution of the large rainfall rates now being considered.

Figure 1 presents the median profiles obtained by Donaldson. The figure suggests that the median rainfall rate is nearly constant to about 6 km and then decreases rapidly. Variation of median rainfall rate with height is not quite what is needed — the assessment of the variation in frequency of occurrence of a specific rainfall rate as height varies — though of course Figure 1 does suggest that there is little variation up to about 6 km. Again Donaldson gives us some guidance by presenting frequency distributions for specified reflectivity values at levels of 5000, 20 000, 30 000, and 40 000 ft.* These frequency distributions yield, approximately, the rainfall rate distributions summarized by Table III.

TABLE III—PERCENTAGE OF NEW ENGLAND THUNDERSTORMS WHICH HAVE PRECIPITATION RATES EQUAL TO OR EXCEEDING SPECIFIED VALUES

Height	Precipitation rate (mm/h) 25	50	100
km		*per cent*	
1·5	55	30	20
6	40	20	10
9	10	3	1
12	5	1	<1

* 1000 ft ≈ 305 m.

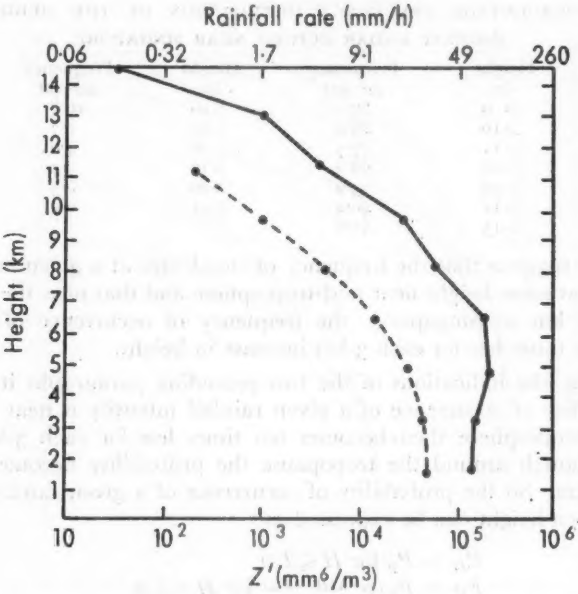


FIGURE 1—MEDIAN VALUES OF RADAR REFLECTIVITY AND OF EQUIVALENT RAINFALL RATE FOR NEW ENGLAND THUNDERSTORMS

(After Donaldson[3])

- - - - Rain, 182 cases. ——— Hail, 51 cases.

Z' = radar reflectivity of small spherical water drops which would have the same total backscattering cross-section as the measured echo

Table III refers to total precipitation whereas it is intended to determine variations in rainfall only. It is seen that the fall-off with height in the frequency of occurrence of a given total precipitation rate is most marked for high values of that rate. Now, the largest precipitation rates are associated with the largest updraughts and so with the lowest likelihood of drops becoming frozen by a given height. Hence freezing will affect relatively more raindrops at precipitation rates of 25 mm/h than of 50 mm/h, or again of 100 mm/h, and so will tend to even out the differences between the columns of Table III when the probability of rainfall only is being considered. Again this implies that column 4 of the table is the most likely to indicate how the frequency of occurrence of a given rate of rainfall falls off with height. Thus, at least for New England storms which extend to over 12 km, it seems that the probability of occurrence of a given rate of rainfall is nearly constant to about 6 km and then becomes 10 times less for each 3-km increase in height.

As indicated above, the overall probability of occurrence of a given rainfall rate depends also on the height distribution of shower cloud tops. Radar studies indicate these distributions and, for example, Moore (unpublished) has obtained the following percentage frequencies for radar echoes around Singapore.

TABLE IV—PERCENTAGE FREQUENCY DISTRIBUTION OF THE HEIGHTS OF THE HIGHEST RADAR ECHOES NEAR SINGAPORE

Height *km*	Frequency *per cent*	Height *km*	Frequency *per cent*
$\geq$ 9	85·1	$\geq$16	16·6
$\geq$10	83·0	$\geq$17	9·7
$\geq$11	77·7	$\geq$18	4·0
$\geq$12	68·2	$\geq$19	1·4
$\geq$13	53·2	$\geq$20	0·5
$\geq$14	40·2	$\geq$21	0·2
$\geq$15	27·6		

Table IV suggests that the frequency of cloud tops at a given height begins to decrease at some height near mid-troposphere and that near the tropopause (around 16 km at Singapore) the frequency of occurrence of cloud tops becomes ten times less for each 3-km increase in height.

Combining the indications of the two preceding paragraphs it seems that the probability of occurrence of a given rainfall intensity is near constant to about mid-troposphere then becomes ten times less for each 3-km increase in height though around the tropopause the probability becomes ten times less in 1·5 km. So the probability of occurrence of a given rainfall intensity, P_H, at a given height can be expressed as

$$P_H = P_p \text{ for } H \leqslant T/2$$
$$P_H = P_p 10^{-k(H-T/2)} \text{ for } H > T/2 \qquad \ldots (2)$$

where T = tropopause average height and k has a value somewhere between $\frac{1}{3}$ and $\frac{2}{3}$.

In using the relation (2) above it must be noted that since water drops tend to freeze spontaneously even without nuclei when the temperature approaches −40°C then it is likely that all raindrops will be frozen at heights somewhere about 13 km so rainfall probabilities above 13 km should approximate to zero. However, at heights above 13 km or so mushy hail may produce effects equivalent to those of rain and so the use of relation (2) may still be informative.

Estimates of rainfall encounters for Concorde. Relations (1) and (2) can be used together with the appropriate values of P_p, R and T to determine probabilities of aircraft encounters with rainfall of a specified intensity. It is necessary to know the height–speed profile of the aircraft, and for Concorde the following values are indicated by probable operational routines :

Height *km*	Speed *m/s*	Height *km*	Speed *m/s*
3	200	12	375
6	250	15	500
9	300	18	600

Using these values and relevant rainfall data for Heathrow, Singapore and Freetown, the intensity of rain likely to be met once in 10^5 flight hours has been determined. Figure 2 presents the results using two values, i.e. $\frac{1}{3}$ and $\frac{2}{3}$, for the factor k in relation (2). It is thought that the pecked lines corresponding to $k = \frac{2}{3}$ are more likely to correspond to actual experience especially at the highest levels, though the solid lines corresponding to $k = \frac{1}{3}$ may provide safer planning guidance.

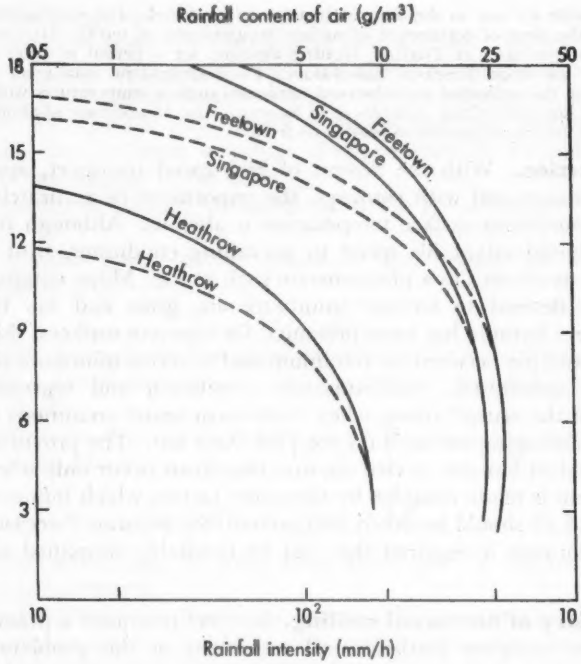


FIGURE 2—INTENSITY OF RAIN MET ONCE IN 10^5 FLIGHT HOURS (ALL AT CONSTANT HEIGHT)

——— Assumes $P_H = P_p \times 10^{-\frac{1}{2}(H-T/2)}$

- - - Assumes $P_H = P_p \times 10^{-(2/3)(H-T/2)}$

REFERENCES

1. BRIGGS, J. and HARKER, J. A.; Estimates of the duration of short-period rainfall rates based on clock-hour values. *Met Mag, London*, **98**, 1969, pp. 246–252.
2. HAMILTON, P. M.; Vertical profiles of total precipitation in shower situations. *Q J R Met Soc, London*, **92**, 1966, pp. 346–362.
3. DONALDSON, R. J. D.; Radar reflectivity profiles in thunderstorms. *J Met, Lancaster, Pa*, **18**, 1961, p. 292.

551.509.323:551.525.2:625.7

AN OBJECTIVE AID FOR ESTIMATING THE NIGHT MINIMUM TEMPERATURE OF A CONCRETE ROAD SURFACE

By JOHN E. THORNES*

Summary. Many factors influence nocturnal cooling of a concrete surface. This investigation has confirmed that the minimum temperature can be estimated by a simplified mathematical approach which is described. The important variables are the sunset surface temperature, length of night, overnight wind speed, cloud type and amount, and dew-point. When estimations were below 0·0°C the theoretical formula gave minima which were too low, and on the basis of actual data a correction was applied to allow for the release of latent heat.

* Geography Department, University of Manchester.

A chart suitable for use on the forecast bench was produced. The method can also be used to estimate the time of occurrence of surface temperatures of 0·0°C. Data on road surface temperatures from sites at Tuxford, Nottinghamshire, for a period in 1968 and 1969 were provided by the Road Research Laboratory. For independent data good agreement was found between the estimated and observed minimum surface temperatures with a r.m.s. error of 0·76 degC but none of the variables were forecast. Also an accuracy of almost 100 per cent was obtained for the estimation of frost or no frost.

Introduction. With the advent of high-speed transport, associated both with motorways and with runways, the importance of accurately forecasting the night minimum surface temperature is obvious. Although the motorway motorist should adapt his speed to prevailing conditions, frost and ice are not always as obvious as a phenomenon such as fog. Many empirical formulae have been devised to forecast minimum air, grass and soil temperatures, but no direct formula has been presented for concrete surfaces. Many correlations, for example between air minimum and concrete minimum temperatures, have been attempted. Unfortunately correlation and regression methods often fail at the crucial times, when frosts form under conditions special to an occasion; averaging methods do not pick these out. The provision of a useful and economical forecast service requires that frosts occur only when predicted. The problem is made complex by the many factors which influence nocturnal cooling, and all should be taken into account for accurate forecasts. A mathematical approach is required that can be justifiably simplified when used in practice.

The theory of nocturnal cooling. Reuter[1] produced a practical solution to a rather complex mathematical treatment of the problem to forecast minimum soil temperatures. He modified an earlier approach by Brunt,[2] to take into account the effect of wind speed. Reuter noted that the conditions which favour nocturnal cooling of the ground surface are :

(a) Absence of wind.
(b) Clear skies.
(c) Low vapour pressure in the atmosphere above the surface.
(d) Low coefficient of thermal conductivity and low specific heat of the surface.

Reuter's basic formula is

$$\Delta T = F(E + Bk_g + (\gamma - \gamma_d)\, c_p A)\, t^{\frac{1}{2}},$$

where ΔT = fall in temperature at the ground surface from sunset to sunrise during a night of length t

$$F = \frac{2}{\pi^{\frac{1}{2}}} \; \frac{1}{(\rho_g c_g k_g)^{\frac{1}{2}} + c_p(\rho A)^{\frac{1}{2}}}$$

ρ_g = density of soil
c_g = specific heat of soil
k_g = coefficient of heat conductivity of soil
c_p = specific heat of air
ρ = density of air
A = coefficient of eddy conductivity in air
E = net outgoing long-wave radiation from surface under cloudless conditions
B = lapse rate in soil at sunset
γ = lapse rate in air at sunset
γ_d = dry adiabatic lapse rate.

The following assumptions should be noted:

(a) Nocturnal radiation is constant during the night. (In fact it falls by about seven or eight per cent between sunset and sunrise.[3])

(b) Specific heat, density and coefficient of heat conductivity of ground surface are constant with respect to depths and time during the night.

(c) Initially there is linear variation of temperature in the vertical in the ground surface and in the air.

(d) The coefficient of eddy conductivity in the air is constant during the night.

Reuter also made allowance for cloudiness when testing his formula. He replaced the term E by

$$E_w = E(1 - w\,k),$$

where E_w is the observed net loss of radiation from the ground when w tenths of the sky are covered with clouds, and the factor k depends on the height and type of cloud.

The expression for E_w was the one used by Dorno, but a better estimate has been given by Mizon:[4]

$$E_n = E(1 - \sum_{i=1}^{r} n_i k_i) = KE,$$

which allows for an estimate E_n when there are r layers of cloud with amount n_i and factor k_i for layer i.

Reuter had difficulty in finding accurate soil constants $k_g c_g \rho_g$ as these vary with moisture content as well as with constituents. Also he used screen air temperatures T instead of ground surface temperatures in estimating E when using Ångström's formula

$$E = \sigma\, T^4(0{\cdot}194 + 0{\cdot}236 \times 10^{-0.069e}),$$

where σ is Stefan's constant $8{\cdot}132 \times 10^{-11}$ cal/(cm^2 (degC)^4 min) and e is vapour pressure at sunset in millimetres of mercury (1 cal = 4·1868 J; 1 mm Hg ≈ 1·33 mb).

For a concrete surface it seems reasonable to use a modified version of Reuter's formula

$$\Delta T = F(E + B\,k_c + (\gamma - \gamma_d)\,c_p\,A)t^{\frac{1}{2}},$$

$$\text{where } F = \frac{2}{\pi^{\frac{1}{2}}}\,\frac{1}{(\rho_c c_c k_c)^{\frac{1}{2}} + c_p(\rho A)^{\frac{1}{2}}},$$

$$E = \sigma\, T_c^4\,(0{\cdot}194 + 0{\cdot}236 \times 10^{-0.069e}),$$

$$T_c = \text{surface temperature of concrete at sunset,}$$

and ρ_c, c_c, k_c are values of density, specific heat and coefficient of heat conductivity of concrete.

Reuter also showed that the terms $Bk_g + (\gamma - \gamma_d)c_pA$ are about 10 times smaller than E and can be neglected. Likewise $Bk_c + (\gamma - \gamma_d)c_pA$ may be neglected and the equation may be simplified to

$$\Delta T = Ft^{\frac{1}{2}}\,E.$$

Finally an allowance for cloud can be introduced by multiplying E by a factor K allowing for cloudiness; thus

$$\Delta T = Ft^{\frac{1}{2}}KE.$$

Data used. Data on road surface temperatures were provided by the Road Research Laboratory. Two sites near Tuxford, Nottinghamshire, on the A1, were used. At 'Tuxford North' a concrete slab nine inches deep, of the same structure as the road to which it is adjacent, has thermocouples embedded in it. The thermocouple at half-inch depth was taken to represent the surface temperature. The slab is sheltered somewhat from the north and west by observers' huts. On the whole, the continuous recordings made by the copper–constantan thermocouples were good, but because of breakdowns only the winter 1968/69 was completely recorded.

The site at 'Tuxford South' has thermocouples embedded in the road and the road is on an embankment. However, records for this site are of poorer quality than those from Tuxford North; because of this, and the fact that Tuxford South is affected by other variables such as passage of transport and the accumulation of salt and grit in winter, results from Tuxford North were examined in most detail.

For each night considered the sunset temperature at a depth of half an inch was recorded, and the minimum, thus giving the fall in temperature overnight (ΔT). Strictly one should record the fall from sunset to sunrise, but little difference was observed between the minimum and the sunrise temperature.

The nearest meteorological station with a similar terrain is at Finningley, about 20 miles ($\approx$ 32 km) to the north. In order to obtain the average dew-point temperature, wind speed and cloud cover for each night, the three-hourly records at Finningley were examined. Data from Watnall, some 20 miles west and in the Pennine foothills were also examined, and an average taken. However, the Finningley data alone proved more representative because of its similar environment.

Data for the winter 1968/69 were analysed, and also for July 1969. The months October, November, December, January and March were used as development data, and February, April and July as test data. (The February surface data were from Tuxford South during a period when the slab at Tuxford North was covered with snow.)

For January the Finningley data for 15 , 18 , 21 , 00 , 03 , 06 and 09 GMT each night were averaged, whereas in July only the 21 , 00 and 03 data each night were required.

The fact that a meteorological station 20 miles away had to be used, shows how little research has gone into this problem. It is only recently that stations began recording a concrete minimum temperature, but the value of these measurements has yet to be proved.

Practical application of the formula.

(a) *The estimation of F.* The function F is a characteristic function of the concrete and varies with A the coefficient of eddy conductivity. No accurate data relating wind speed and coefficient of eddy conductivity could be found for the conditions considered and a relationship had to be worked out. Observed values of ΔT, t and KE for the site at Tuxford, Nottinghamshire, were used to determine F from the equation

$$\Delta T = Ft^{\frac{1}{2}} KE,$$

and F was plotted against wind speed (Figure 1) using the development data, and a curve of best fit was drawn. The test data were then examined and values of F obtained for various wind speeds. These values were incorporated

To face page 16

PLATE I—HOT-AIR BALLOON 'CHRISTABELLE'

This balloon is owned and piloted by Wing Commander G. F. Turnbull, O.B.E., A.F.C., who supplied the photograph (see page 25).

Photographs by No. 42 Squadron, RAF

PLATE II—WATERSPOUT JUST NORTH-EAST OF BISHOP ROCK LIGHTHOUSE PHOTOGRAPHED FROM A SHACKLETON AIRCRAFT AT ABOUT 06 GMT ON 23 MAY 1971

Some of the Isles of Scilly can be seen in the background. The north-westerly airstream was unstable and main cloud base was estimated to be about 1500 feet. The crew of the aircraft thought that the diameter of the spout at the surface was about 20 feet.

PLATE II—*continued*

To face page 17

PLATE III—AWARDS TO CIVIL AIRLINE PILOTS

From left to right: Mrs J. B. Linton, Captain J. B. Linton, Director-General of the Meteorological Office, Captain and Mrs W. C. Parke (see page 29).

into Figure 1 and a curve drawn which represents the whole data. The two curves differ little and only at high wind speed. At low wind speeds an anemometer reads too low because of friction and inertia effects and the curve derived from the data was adjusted accordingly (curve C).

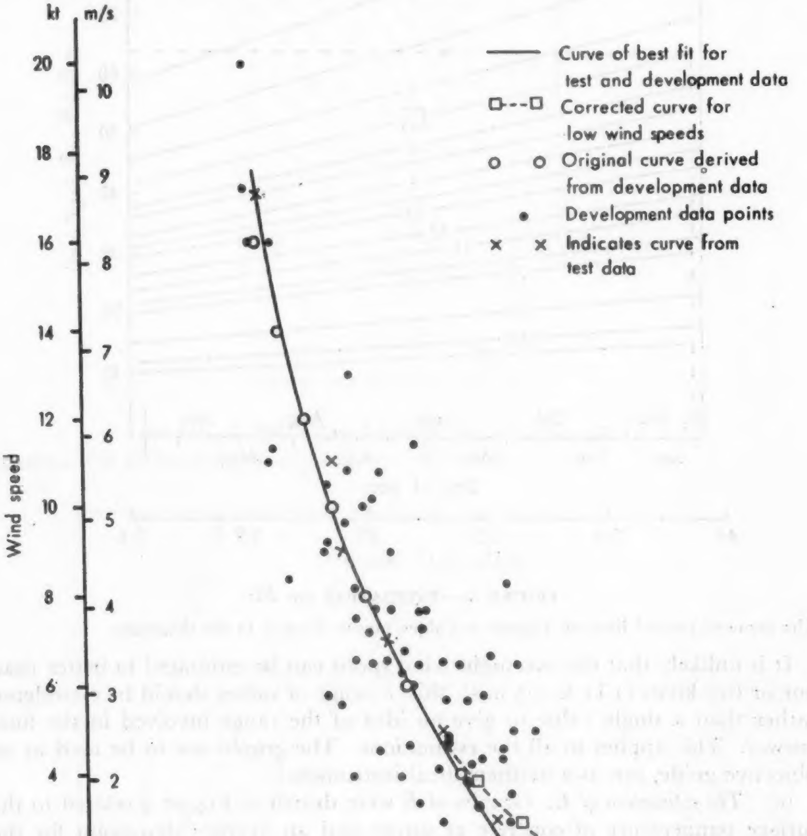


FIGURE 1—GRAPH RELATING WIND SPEED TO FUNCTION F FOR CONCRETE

Note that F is given in c.g.s. units, $s^{\frac{1}{2}}cm^2degC/cal$, if E is given in units of $cal/(cm^2 \min)$ and t is given in hours.

(b) *The estimation of $Ft^{\frac{1}{2}}$.* From the curve relating F to wind speed a series of curves can be drawn (Figure 2) giving $Ft^{\frac{1}{2}}$ for given wind speeds and given duration of night. The scale for $t^{\frac{1}{2}}$ is linear and a scale for the time of year has been added for convenience.

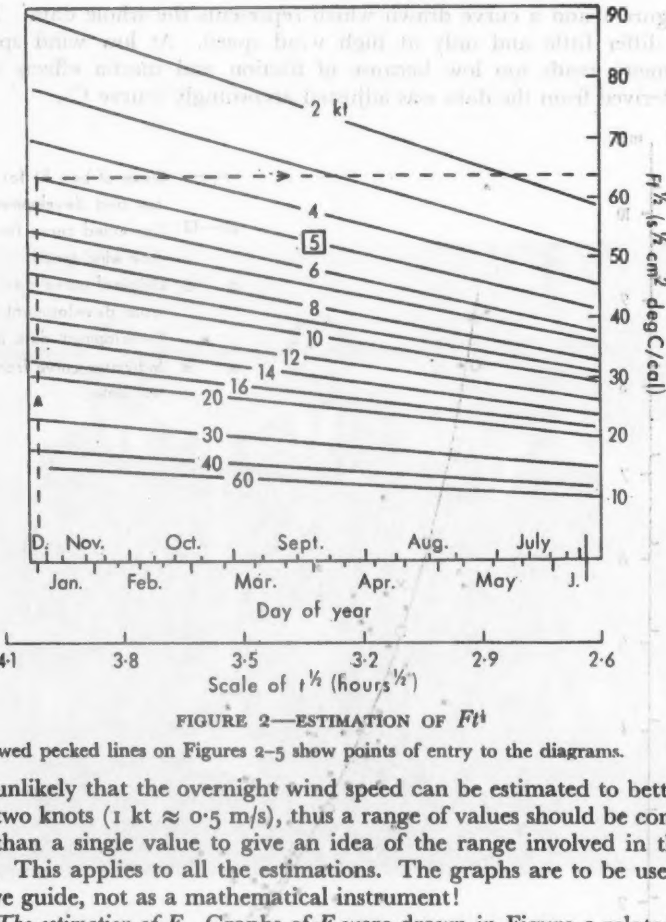


FIGURE 2—ESTIMATION OF $Ft^{\frac{1}{2}}$

The arrowed pecked lines on Figures 2–5 show points of entry to the diagrams.

It is unlikely that the overnight wind speed can be estimated to better than one or two knots (1 kt ≈ 0·5 m/s), thus a range of values should be considered rather than a single value to give an idea of the range involved in the final answer. This applies to all the estimations. The graphs are to be used as an objective guide, not as a mathematical instrument!

(c) *The estimation of E.* Graphs of E were drawn in Figure 3 related to the surface temperature of concrete at sunset and an average dew-point for the night instead of vapour pressure. The dew-point temperature does not usually vary much during the night. Moreover, a formula by Swinbank[5] estimates the outgoing radiation E to be a function of temperature only, i.e.

$$E = 5{\cdot}31 \times 10^{-14}\, T^6 \text{ mW/cm}^2.$$

Thus a variable may be removed from the argument, but this possibility has not been pursued.

(d) *The estimation of K.* Reuter gives Dorno's factors for 1/10 cloud of various types as: Cs 0·031; As 0·063; St 0·085; Ns 0·099. These factors were taken as factors for $\frac{1}{8}$ cloud and the resulting values of K were similar to the values of K used by Mizon. Graphs were drawn in Figure 4 to obtain K for various types and amounts.

$$\text{As } K = 1 - \sum_{i=1}^{r} n_i k_i\,, \quad K = \left[\sum_{i=1}^{r} K_i\right] - (r-1).$$

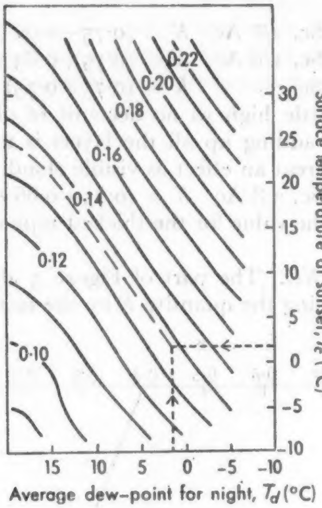


FIGURE 3—ESTIMATION OF E

Isopleths of E are drawn at intervals of 0·01 cal/(cm² min).

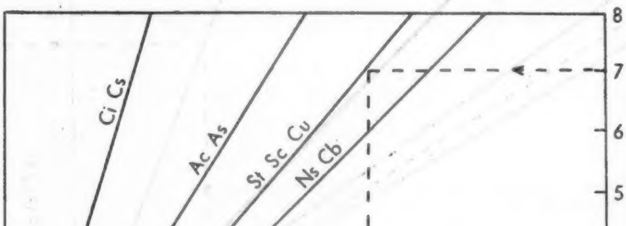


FIGURE 4—ESTIMATION OF K

Problems occur when more than one layer of cloud is expected, e.g. the total cloud cover may be 6/8 made up of 3/8 Cu, 4/8 Sc, 3/8 Ac. It would be wrong just to add up the components as 2/8 of the sky is clear. Obviously as the Cu is the lowest layer, it is all visible. The remaining 3/8 is either made up of 1/8 Sc and 2/8 Ac, or 2/8 Sc and 1/8 Ac, or 3/8 Sc.

These give :

(1) 3/8 Cu, 1/8 Sc, 2/8 Ac $K = (0{\cdot}75+0{\cdot}92+0{\cdot}87)-2 = 0{\cdot}54$
(2) 3/8 Cu, 2/8 Sc, 1/8 Ac $K = (0{\cdot}75+0{\cdot}83+0{\cdot}94)-2 = 0{\cdot}52$
(3) 3/8 Cu, 3/8 Sc $K = (0{\cdot}75+0{\cdot}75)-1 = 0{\cdot}5$

These values are a little high as no account of obscured cloud is taken. The value obtained by adding up all the layers is too low, as the obscured cloud does not have as great an effect as visible cloud.

(4) 3/8 Cu, 4/8 Sc, 3/8 Ac $K = (0{\cdot}75+0{\cdot}66+0{\cdot}81)-2 = 0{\cdot}22$

A guide is to look at the value for the thickest type of cloud, i.e. Ns and Cb for $6/8 = 0{\cdot}4$.

(e) *The estimation of KE.* The part of Figure 5 above the thick diagonal is a nomogram for reducing the quantity E by the factor K to give KE.

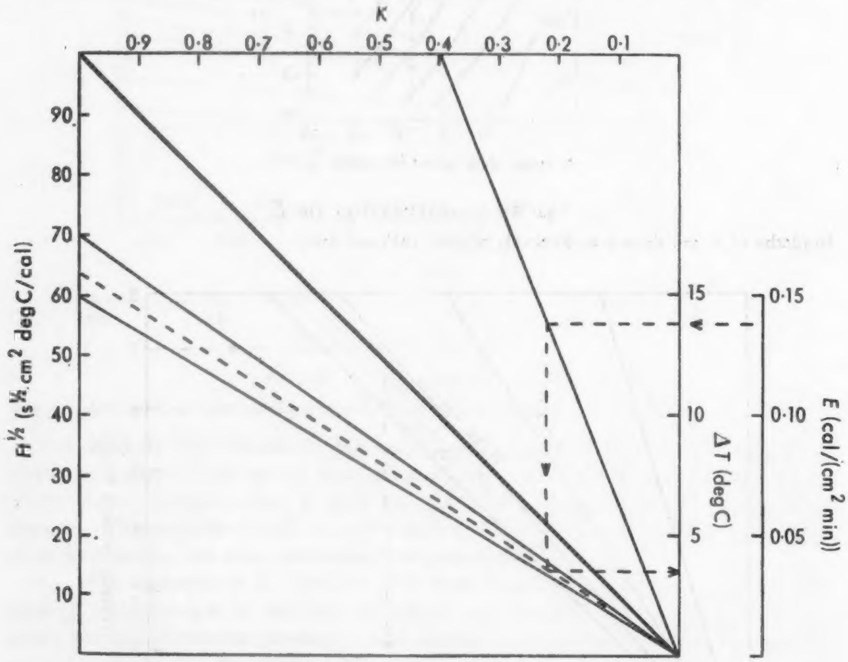


FIGURE 5—ESTIMATION OF KE AND $Ft^{\frac{1}{2}} \times KE$

(f) *The estimation of* $Ft^{\frac{1}{2}} \times KE$. The part of Figure 5 below the thick diagonal is a nomogram for obtaining $Ft^{\frac{1}{2}} \times KE$. The scale of KE when multiplied by $Ft^{\frac{1}{2}}$ gives the scale for ΔT in degrees Celsius.

Comparison of estimations of ΔT and measurements of ΔT. The diagrams (Figures 2–5) were used to estimate ΔT from estimates of wind speed, cloud amount and type, and dew-point, along with known sunset temperature and length of night. Nights were not included if snow lay on the ground, if a front passed over the sites, or if marked wind changes occurred suggesting large-scale advection. In Figure 6 the estimated ΔT has been plotted against actual measurement of ΔT and the full line is the line giving

estimations equal to actual measurements. For nights with frost at the concrete surface it was found that the forecast temperature drop was nearly always too great and a correction was applied, based on the small-pecked line in Figure 6 indicating the best estimate of the actual for various forecasts below zero.

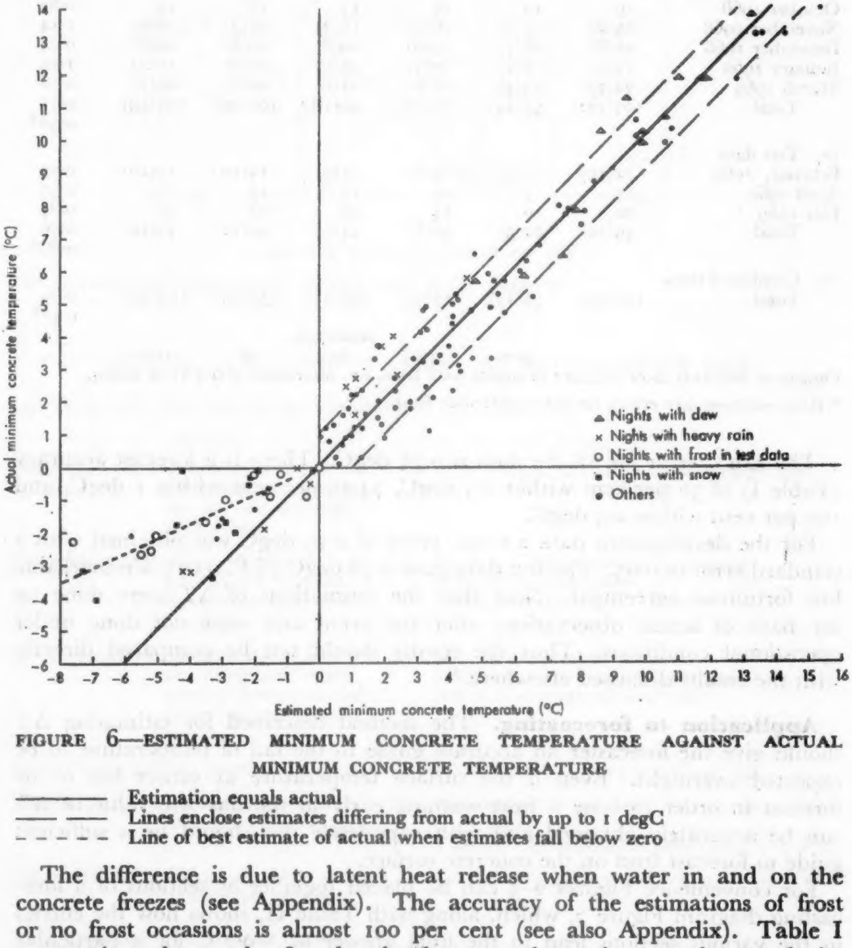


FIGURE 6—ESTIMATED MINIMUM CONCRETE TEMPERATURE AGAINST ACTUAL MINIMUM CONCRETE TEMPERATURE

——— Estimation equals actual
— — Lines enclose estimates differing from actual by up to 1 degC
- - - - - Line of best estimate of actual when estimates fall below zero

The difference is due to latent heat release when water in and on the concrete freezes (see Appendix). The accuracy of the estimations of frost or no frost occasions is almost 100 per cent (see also Appendix). Table I summarizes the results for the development data, the test data and the combined data and gives the number of estimates of ΔT which were within various ranges of error.

Corrected results for nights when the actual minimum fell below 0°C, for the development months gave root-mean-square error = 0·38 degC, and for the test data r.m.s. error = 0·66 degC. The accuracy for the test data is notable because frost only occurred on the days considered in February when Tuxford South data were used. Thus the amount of traffic and the presence of salt and grit, etc. (not taken into account) would appear to have little effect.

TABLE I—FREQUENCY OF ESTIMATES OF ΔT WITHIN DEFINED RANGES

Period	No. of estimates	Range of ΔT (degC) ±0·5	±1·0	±1·5	±2·0	±2·5	Root-mean-square error
				frequency			
(a) Development data							
October 1968	19	10	14	17	18	19	0·83
November 1968	25(2)	7(2)	16(2)	19(2)	25(2)	25(2)	1·14
December 1968	20(8)	16(7)	19(8)	20(8)	20(8)	20(8)	0·24
January 1969	17(2)	8(1)	10(1)	15(2)	16(2)	17(2)	1·03
March 1969	22(7)	13(4)	18(6)	21(6)	22(7)	22(7)	0·52
Total	103(19)	54(14)	77(17)	92(18)	101(19)	103(19)	0·75 0·38*
(b) Test data							
February 1969	12(10)	5(5)	9(8)	11(9)	12(10)	12(10)	0·73
April 1969	15	7	13	13	15	15	0·55
July 1969	22	10	14	20	22	22	0·87
Total	49(10)	22(5)	36(8)	44(9)	49(10)	49(10)	0·76 0·66*
(c) Combined data							
Total	152(29)	76(19)	113(24)	136(27)	150(29)	152(29)	0·75 0·51*
				percentages			
		50·0	74·25	89·5	98·7	100·0	

Figures in brackets show number of nights with frost, i.e. minimum of 0·0°C or below.

* Root-mean-square errors for the nights with frost.

The r.m.s. error for all the data is 0·75 degC. There is a forecast accuracy (Table I) of 50 per cent within 0·5 degC, 74·25 per cent within 1 degC, and 100 per cent within 2·5 degC.

For the development data a r.m.s. error of 0·75 degC was obtained with a standard error of 0·05. The test data gave 0·76 degC (S.E. 0·07), a remarkable but fortuitous agreement. Note that the estimations of ΔT were done on the basis of actual observations after the event and were not done under operational conditions. Thus the results should not be compared directly with the results discussed elsewhere.[6]

Application to forecasting. The method described for estimating ΔT should give the forecaster an accurate guide to the fall of temperature to be expected overnight. Even if the surface temperature at sunset has to be forecast in order to issue a frost warning early in the day the value of ΔT can be accurately obtained and with experience this should be a sufficient guide to forecast frost on the concrete surface.

For convenience Figures 2–5 can be placed together as sections of a forecasting diagram Figure 7, which, along with Table II, shows how the entries in the various sections lead to the final answer of −0·7°C for a particular night in December 1968 (the actual minimum was −0·9°C).

An estimate can be made of the time of frost formation if the formula is considered in the form $\Delta T_t = Ft^{\frac{1}{2}}KE$ where ΔT_t is the fall in temperature after time t, where t varies from 0 to the length of night. If ΔT_t equals the surface temperature at sunset then t can be obtained from Figure 7 by the method given in Table II(b).

Discussion. From the results it appears that all the suggested factors that effect nocturnal cooling (T_d, T_c, t, wind speed, K) play important roles, and should be taken into account. Mizon[4] in an investigation into soil

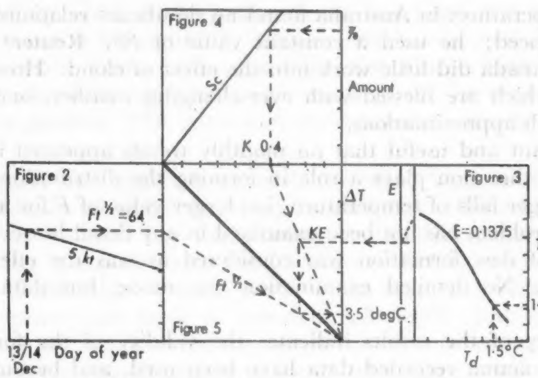


FIGURE 7—ESTIMATION OF ΔT

The arrowed pecked lines show points of entry to the diagrams.

TABLE II—APPLICATION OF METHOD ON 13/14 DECEMBER 1968

(a) To forecast minimum surface temperature

	Method	Result
From Figure 2 :	**obtain value of $Ft^{\frac{1}{2}}$ according to day of year and forecast overnight wind speed**	**Wind 5 knots gives $Ft^{\frac{1}{2}}$=64 stcm²degC/cal**
From Figure 4 :	**obtain value of K according to forecast cloud cover and type overnight**	**8/8 Sc all night clearing by morning Take 7/8 Sc as average 7/8 Sc gives K=0·4**
From Figure 3 :	**obtain value of E according to forecast average dew-point and surface temperature at sunset**	**Dew-point overnight 1·5°C Surface temperature 1·9°C at sunset Hence E=0·1375 cal/(cm²min)**
From Figure 5 above diagonal :	**obtain KE**	**Intersection of K=0·4 and E=0·1375**
From Figure below diagonal:	**obtain $KE \times Ft^{\frac{1}{2}}$ and read off value of ΔT**	**Intersection of KE with $Ft^{\frac{1}{2}}$=64 gives ΔT= 3·5 degC This gives a temperature below zero (−1·6°C)**
From Figure 6 :	**obtain correction on basis of small-pecked line**	**Corrected minimum temperature= −0·7°C.**

(b) To forecast time of onset of frost

From Figure 4 :	**8/8 Sc probably persisted until frost For 8/8 Sc, K = 0·32**
From Figure 3 :	**Dew-point overnight = 1·5°C Sunset surface temperature = 1·9°C Hence E = 0·1375**
From Figure 5 above diagonal :	**Intersection of K = 0·32 and E = 0·1375 gives KE**
From Figure 5 below diagonal :	**Intersection of KE and ΔT = 1·9 degC gives $Ft^{\frac{1}{2}}$ = 46·5**
From Figure 2 :	**Intersection of $Ft^{\frac{1}{2}}$ = 46·5 and wind 5 knots gives $t^{\frac{1}{2}} \approx 2{\cdot}95$ and t = 8·7 hours (With sunset at 1550 GMT frost can be expected soon after midnight)**

minimum temperatures in Australia found no significant relationship between F and wind speed; he used a constant value of $Ft^{\frac{1}{2}}$. Reuter[1] working in Austria and Canada did little work into the effect of cloud. However, in the British Isles, which are blessed with ever-changing weather, one can afford to make no such approximations.

It is significant and useful that no monthly trends appeared in Figure 1; however, wind direction plays a role in forming the distribution. Northerly winds gave bigger falls of temperature (i.e. larger value of F for a given wind speed). This problem has not been examined in any detail however.

The effect of dew formation was considered as was the effect of heavy overnight rain. No detailed examination was made, but data are shown in Figure 6.

The accuracy of the results indicates the validity of the formula used. However, only actual recorded data have been used, and because of a lack of readily available data no forecasting has been attempted. In order to facilitate further research the following recommendations are made:

(a) This investigation has shown that the sunset surface temperature is a vital parameter in determining whether or not frost will occur. Concrete temperatures should be taken at hourly intervals as well as at sunset. The minimum on its own is of little use as it gives no indication of the fall in temperature from sunset. Of course a continuous recording thermometer would be best, and for experimental purposes one ought to be installed at some meteorological stations.

(b) Research should be undertaken to derive values of F for tarmac, and other surfaces. This could easily be done.

(c) For use as a forecasting tool the method must be extended to include a forecast of the sunset temperature so that a forecast of the minimum temperature can be issued by 15 GMT at the latest. It seems that in winter the surface sunset temperature bears a strong correlation to the afternoon maximum surface temperature. This has yet to be verified however.

REFERENCES

1. REUTER, H.; Forecasting minimum temperatures. *Tellus, Stockholm*, **3**, 1951, pp. 141–147.
2. BRUNT, D.; Physical and dynamical meteorology. Cambridge, Cambridge University Press, 1939.
3. HASCHE, E.; Zur Messung der langwelligen Himmels und Erdstrahlung. *Gerlands Beitr Geophys, Leipzig*, **42**, 1934, pp. 228–231.
4. MIZON, E. A.; An objective aid for minimum temperature forecasts — Alice Springs, N. Territory. *Aust Met Mag, Melbourne*, **38**, 1962, pp. 20–31.
5. SWINBANK, W. C.; Long wave radiation from clear skies. *Q J R Met Soc, London*, **89**, 1963, pp. 339–348.
6. PARREY, G. E., RITCHIE, W. G. and VIRGO, S. E.; Minimum temperatures at the surfaces of concrete roads and concrete slabs. *Met Mag, London*, **100**, 1971, pp. 27–31.

APPENDIX

Correction to estimated minimum concrete temperature for values below 0·0°C

One of the unexpected results of estimating the minimum concrete temperature by this method, is shown clearly in Figure 6. The accuracy for the estimation frost/no frost is almost 100 per cent. Also as noted in the text, there is a

mechanism acting which makes estimates too low when the estimated minimum temperature is below 0·0°C. Estimates are low because there is release of latent heat when frost occurs. The correction line in Figure 6 is the line of best fit for the data used, but more research will be required before an accurate fix is possible. The correction line takes into account this release of latent heat.

The correction line cannot however be extended back to the origin 0; a discontinuity occurs when the actual minimum is just below 0·0°C, i.e. marked over-forecasting occurs. The explanation of this discontinuity is not fully understood, but it explains why the frost/no frost estimate is so accurate in this sample. In the table of results it was shown that the method of estimation has a root-mean-square error of less than 0·8 degC. Just above 0·0°C in Figure 6 it can be seen that on the whole the formula estimates too high a minimum; however, insufficient data around this region preclude any definite conclusions. When the surface temperature falls to 0·0°C, the moisture both in and on the concrete begins to change state to ice; this takes place with the water at constant temperature around 0·0°C (depending on impurities, etc.) and any further fall of the surface temperature is delayed because of the release of latent heat as the water freezes. The actual minimum is higher than the formula predicts, as energy has been gained from a source not included in the analysis. No attempt was made to include it. This energy is presumably of a greater dimension than that required to change the surface temperature by 0·8 degC (the r.m.s. error), and therefore the discontinuity is marked, and the correction line is offset as shown in Figure 6.

The results support the validity of the present definition of frost, i.e. when the temperature falls below 0·0°C.

Freezing must occur for this process to take place, e.g. if comparatively warm rain falls, less ice will form, and, as can be seen in Figure 6 the results in rain are nearer the line indicating estimate equal to actual minima.

551.509.58:797.5

SOME METEOROLOGICAL AND OTHER ASPECTS OF HOT-AIR BALLOONING

By G. A. SAMUEL

The sport of hot-air ballooning is rapidly gaining popularity in this country and on the continent and becoming decidedly international in character. Organizers of fêtes and festivals are quick to add colour and interest to their social functions by suggesting hot-air balloon races and other displays. This is not surprising since the running cost is fractional compared with the more conventional balloon where one fill of helium, delivered to site, in sufficient quantities to give two or three persons enough lift to perform a successful flight can be as much as £1000 and if hydrogen is used, although the cost is less, the attendant risk is very much greater.

The hot-air balloon is a much cheaper method of becoming airborne. One hour of flight needs about £5 to £7 worth of propane fuel gas. The initial cost of the balloon, trailer and other equipment can be about £2000 but since most balloons are owned by a syndicate of five or more people the

cost to the individual is reduced to a more reasonable figure. Indeed, such a syndicate is required since preparing a balloon for a flight is certainly not a single-handed operation. In fact the difficulties seem to mount as a power function of the surface wind speed. However, there are many adventurous souls who spend this sort of sum on their hobby, for example boat owners. The tranquillity of a balloon flight after the hurly-burly of modern life has a great appeal but the intermittent roar of the burner of a hot-air balloon does detract somewhat from the peacefulness of balloon flight.

The hot-air balloon can be obtained in a variety of sizes, some of the most popular being around 56 000 to 64 000 cubic feet ($\approx$ 1700 m^3) which will carry from two to four persons. The surface area of these balloons is around 900 to 1200 square yards ($\approx$ 800 m^2).

The balloon as a carrying vehicle is reputed to have quite a high safety factor but although the safety factor appears to be diminished somewhat by the antics of some of the daring people who fly them, the reverse is true because not only are they daring but they are also very safety-conscious and responsible people. The Pilots Examiner of the Department of Trade and Industry sees to this.

The fabric of which the balloon is made is high-tensile nylon of a special rip-stop weave, proofed with polyurethane containing, according to the manufacturers, 'maximum ultra-violet retardant'. The balloons, which in most cases are multicoloured, look very gay when fully inflated. The main loads on the envelope are carried on nylon tapes whilst the fabric of the envelope itself carries a very low stress as a result of its high curvature. The balloon is constructed in such a way that the segments have a bulbous gore, giving it a melon shape (see Plate I). This shape has the advantage of being safest for dynamic loads due to high rates of ascent or descent since it can 'give' in a way in which a flat-gored balloon cannot. Most balloons are also fitted with a lace-up or 'velcro' rip panel and a discharge valve — both of which are operated by a lanyard from the basket. The base of the envelope is open to enable the air trapped within it to be heated and there is usually a distant-reading thermometer giving internal temperatures in the crown of the balloon. The open end is connected to the burner frame by stainless steel wires and the envelope itself is protected by a flame-resistant, replaceable section of material. The flame is contained within the confines of this ring-like tube of material to reduce the likelihood of flame damage. However, surface winds in excess of 10 kt ($\approx$ 5 m/s) during filling cause deformation of a partially filled balloon such that the balloon fabric melts in places if the flame is not doused quickly enough.

The burner which hangs between the balloon and the basket with its nozzle directed into the open end of the balloon runs on liquid propane which is vaporized by pre-heating in a helical tube suspended in the flame. The flame itself is about 4 to 12 feet long and the burner output is around 4 000 000 Btu/h ($\approx$ 1200 kW) but this can vary considerably with ambient temperature. Control of the heating flame is effected by an on/off valve and the rate of burning can be adjusted by a needle valve. Maximum heating at the full available rate would supply enough energy to waft the balloon upwards at 1000 feet/min ($\approx$ 5 m/s) or more. The excess temperature of the air within the envelope is raised to over 90 degC, thus when the ambient temperature is high, as on a warm summer's day, an internal temperature of 110°C may be

required to attain lift-off and a suitable rate of ascent. Most balloons are limited by the tolerance of the fabric to heat, and in fact a maximum ambient temperature of 25°C may make things difficult. A clear winter's day with light surface winds would give better conditions except that the saturation vapour pressure of propane limits the minimum temperature for safe flight (Figure 1). The cylinders of propane which weigh 35 lb ($\approx$ 16 kg) empty and 70 lb full are carried in the passenger basket and connected to the burner by high-pressure, quick-release hose couplings.

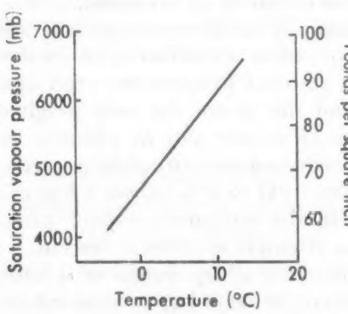


FIGURE 1—VARIATION OF SATURATION VAPOUR PRESSURE OF PROPANE WITH TEMPERATURE

By courtesy of Shell, U.K.

The basket is of traditional design being made of willow and cane with buffalo-hide protection at the edges. No doubt these conventional materials will be replaced by light-weight plastics in the not-too-distant future, but balloonists are loath to make this change since the manufacture of baskets is performed for the most part by blind workers. In any case they claim that there is a goodly amount of 'give' in a basket which cushions the landing. Support is by stainless steel wires which pass in a continuous loop under the basket, embodied in the weave. Carrying loops facilitate handling and launching especially in strong surface winds when helpers must walk with the inflated balloon during the launching process.

An interesting innovation by a Swiss group gives support to the burner by means of a rigid frame and on landing the balloon is immediately released from the basket. A restraining cord is attached to the outside of the crown of the balloon, this causes the balloon to invert with its open end upwards. Another static line rips a large panel from the balloon and thus hot air and consequent ability to lift is lost very rapidly — the envelope emptying and fluttering neatly downwind. The total weight of the rig is about 350 lb to which must be added the weight of the crew and the fuel.

The meteorologist, whether professional or amateur is most useful to the would-be balloonist and much can be learnt by close liaison and exhaustive pre-flight discussions and briefings. The meteorological problem of forecasting conditions suitable for flight of these balloons concerns both surface and upper air winds and temperatures; for example an ambient temperature in excess of 25°C — in some cases — reduces the safety factor below acceptable limits. The excess temperature needed to give adequate lift may be more than the fabric is able to tolerate.

It is thought that should the burner become accidentally extinguished, escaping propane, especially under conditions of low temperatures and high humidity, could cause the formation of ice on the nozzle and so alter its profile as to inhibit relighting, but no reports of this are known to the author. However, there would be downward heat radiation from within the envelope which would be effective even under descent conditions for some considerable time. The author has noticed frost forming on feed pipes and is of the opinion that junctions and unions with varying bore may well be the cause of some otherwise inexplicable loss of power on occasions.

Heat is lost quite quickly from the envelope and unless this heat is maintained the balloon sinks — often accelerating on its downward path. Tables are available where the ambient temperature read against altitude will give a maximum safe load but this is not the only weight-limiting consideration for at low temperatures in winter and at altitude the vapour pressure of propane falls markedly, reducing the output for a given jet size. For example a fall of temperature from 10°C to 0°C causes a loss of 22 pounds per square inch (about 1500 mb) in the saturation vapour pressure. This makes the balloon less responsive to attempts to arrest a descent.

When one considers that the all-up weight of a balloon, including the air it contains, is over two tons ($\approx$ 2032 kg) its momentum is considerably more than its lighter-than-air aspect would suggest.

Static electricity must be produced by the friction of the swirling hot gases inside the balloon and appears as an electrostatic charge outside the envelope; but it appears to be either a small effect or quickly lost through discharge — perhaps by trailing ropes, etc. Lightning risk is not so much of a hazard as with inflammable gases but even so the hot-air balloonist does not want his envelope punctured by whatever means.

Cumulonimbus is definitely unpopular as a near neighbour in the sky and all flights must be under visual meteorological conditions, so flight in any cloud is prohibited. 'Thermals', whilst being welcomed joyfully by glider pilots, are feared and certainly not appreciated by the balloon pilot. In the first place thermals lead to erratic movement and rates of ascent and secondly there is a tendency to cut-off the burner because it is judged, incorrectly, that the rate of ascent is due to the hotness of the air within the envelope. Consequently some of the less-experienced balloonists may find themselves descending rapidly away from the thermal with a cooling balloon and insufficient time to reheat. This, occurring after what has appeared to be a satisfactory rate of ascent illustrates the potential danger. Further, thermals near the ground can start a balloon on an upward rush at the very moment the ripcord has been pulled for a landing. Indeed this happened last year at Nottingham, resulting in an unexpected heavy landing, though happily only bruising was sustained by pilot and crew.

Winds of course play a very, very big part and on-the-spot measurement by hand anemometer and by pilot balloon by the meteorologist is greatly appreciated by the balloonist. Inflation becomes difficult in winds over 6 knots ($\approx$ 3 m/s) and since the envelope is very much larger than a normal sized house a partially filled balloon can quite easily and quite literally get out of hand. By using a pilot balloon and the well-tried tail method to obtain upper winds over the layer to maximum planned-altitude and knowing the estimated duration of flight one is able to dispatch the recovery vehicles to the approxi-

mate point of touch-down, thus saving considerable time, especially under conditions of only moderate visibility.

Incidentally there is a tradition amongst balloonists that a bottle of champagne is supplied by the passenger on his or her first flight for consumption either during or certainly immediately after the flight, which in itself is a heady experience. The youngest qualified balloon pilot in Britain and authoress on the subject is Miss Christine Turnbull (now Mrs Charles Bulmer) and her remark that 'One must be a little mad to take-off under a bubble of hot air sitting in a laundry basket, but the sense of freedom and feeling of exhilaration almost defy description', whilst not describing the people who fly thus, does give an insight into the 'balloonatic fraternity'.

NOTES AND NEWS

Meteorological Office awards to captains and navigators of civil airlines

A system of awards was introduced in 1954 to encourage the making of air reports by civil airline captains and navigators. The awards are in two categories. Books, suitably inscribed, are awarded to the captains and navigators who have provided the best series of reports during the year under review, while captains who have given long and meritorious service in the provision of air reports receive brief cases.

This year brief cases were awarded to Captain J. B. Linton of BOAC and Captain W. C. Parke of BEA by the Director-General at a ceremony held in the Headquarters of the Meteorological Office on Thursday, 23 September 1971 (see Plate III).

REVIEWS

Meteorology (second edition), by A. Miller. 226 mm × 150 mm, pp. iv + 154, *illus.*, Charles E. Merrill Publishing Co., Columbus, Ohio, 1971. Price: £1.

The first edition of this book was published in 1966 and was reviewed in the January 1967 issue of the *Meteorological Magazine.* The book is one of a series, the Merrill Physical Science Series, devised to provide integrated inter-disciplinary courses for the scientific education of non-science students in the U.S.A., and admirably achieves its purpose.

There is evidence throughout of minor amendments, additions and rearrangement to good advantage. One particular improvement worth mentioning is the treatment of 'Circulation patterns' as a separate chapter, thus emphasizing still further the author's concern with 'scales of motion' as a basic concept.

The satellite photograph shown in Figure 4.13, on page 108, illustrating a hurricane, is not particularly informative. It would have been very easy to choose a better one for the purpose. Additional satellite photographs could have been included with advantage, one showing the extratropical cloud systems associated with a series of depressions over an extensive area and one of the many excellent ATS photographs over a tropical area.

Undoubtedly, this edition of the book will be more attractive to the reader. The new cover design is colourful, in the modern style and, more important, illustrative of the subject. The quality of the paper is much improved and the adoption of larger print makes the reading easier. Other improvements are the use of the decimal system for numbering the contents of the chapters and the limited use of colour (one only, however) in both text and diagrams.

The book is recommended for use in schools and colleges as an elementary yet authoritative introduction to the subject.

T. H. KIRK

Radar measurement of precipitation rate, by A. M. Borovikov, V. V. Kostarev, I. P. Mazin, V. I. Smirnov and A. A. Chernikov. 245 mm × 173 mm, pp. iv + 112, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1970. Price: £3·40.

In this book the authors first discuss the theoretical possibilities of measuring precipitation using radar, and include a summary of some of the experimental investigations made in other parts of the world. They then describe in detail the observations made by the Central Aerological Observatory of the U.S.S.R. in the Valdai region during 1964–65. In the first chapter several possible methods of using radar techniques to measure precipitation are reviewed and it is concluded, as in the western world, that the most promising practical means is to relate the echo intensity measured over an area to the rate of rainfall. The remainder of this book is concerned with this technique. A reader new to the subject may find this first chapter difficult to follow and it might be more profitable for him to commence with the second chapter, which consists of a clear, but perhaps rather laborious, account of the physical principles of the relationship between echo intensity and precipitation rate. The chapter includes an original derivation of a radar equation which turns out to be practically identical to that derived by Probert-Jones and now used by most other investigators. The remaining three chapters of the book describe the experimental investigation. This account, extending over 73 pages, will be of interest rather to the specialist in the field than to the general reader. The measurements were made using an ARS–3 radar. This radar had a wavelength of 3·2 cm so that some attenuation of the signal must have occurred in heavy rain. This does not appear to have been corrected for and so must have reduced the accuracy of the rainfall estimates at times. The radar was calibrated in terms of rainfall by matching the radar-derived total for the entire season to that recorded by gauges and by assuming that this calibration held for every rain. Echo intensities were measured from photographs of a PPI display using the stepped-gain technique. The rainfall estimates were compared with 12-hour or 24-hour totals recorded by gauge networks over areas of 100 km^2, 400 km^2 and 10 000 km^2. The gauge density for the smaller areas was an impressive 1 gauge per km^2, supplemented by 1 autographic gauge per 4 km^2, and for the larger area one gauge per 100 km^2. In all about 400 comparisons between radar-derived and gauge-derived rainfall totals were made. These are all listed in an appendix. The authors conclude from their results that they can foresee the incorporation of radar

techniques in the routine observation of precipitation. It would be difficult to conclude similarly for this country from their data since the accuracy of the existing gauge network here is superior to the radar accuracy of 30–40 per cent over areas > 100 km². However, the experiment, conducted in 1964–65, does not show the present state of knowledge. During the six years since these measurements further experiments in various countries indicate that with additional precautions, recognized in this book, the accuracy can be improved significantly.

T. W. HARROLD

LETTERS TO THE EDITOR

551.509.323

A comparison of methods of forecasting night cooling at screen level

As one of the joint authors of two of the tests[1,2] referred to in the above article published in the *Meteorological Magazine* of September 1971,[3] I should like to make the following comments :

(a) McKenzie's method also had a low accuracy at Mildenhall presumably for the same reasons which lowered the accuracy of the Saunders method. In the Mildenhall test[1] it was stated that 'as far as accuracy is concerned, there is very little to choose between the methods when applied to Mildenhall. McKenzie's method is quick to handle and is recommended on that account . . .' The choice of a speedy method was the primary object of the comparison because in a busy office (as Mildenhall was at that time) the winter afternoon workload necessitated quick methods for all purposes. The graphical operations of the Saunders method as carried out at Mildenhall occupied more time and much more bench space than McKenzie's method which only required a small piece of cardboard carrying the table of constants.

(b) The conclusion that the Saunders method appears to be least accurate at stations bordering the Fens is supported by some earlier work. Mr Saunders may recall a test of his method carried out at Weston Zoyland in the early 1950s when the results were not encouraging. As the location of Weston Zoyland is in the middle of a former tidal estuary of the River Parrett, the site is akin to those adjoining the Fen country. A similar effect may therefore render the starting data for Weston Zoyland non-representative for the station.

Meteorological Office, Gibraltar J. GORDON

REFERENCES

1. GORDON, J. and VIRGO, S. E.; Comparison of methods of forecasting night-minimum temperatures. *Met Mag, London*, **97**, 1968, pp. 161–164.
2. GORDON, J., PERRY, J. D. and VIRGO, S. E.; Forecasting night minimum air temperature by a regression equation. *Met Mag, London*, **98**, 1969, pp. 290–292.
3. SAUNDERS, W. E.; A comparison of methods of forecasting night cooling at screen level. *Met Mag, London*, **100**, 1971, pp. 280–283.

551.554:551.556:551.453

Sand streets

In his interesting note on 'Sand streets',[1] Mr J. D. Hastings concludes that the absence of longitudinal dune forms over northern Cyrenaica may be attributed to an insufficiency of sand. Observations in the field confirm that this is so. The massive sand accumulations of the Libyan Desert are confined to the region south of the so-called '29th parallel oases', some 300 km away to the south. The terrain between this sand sea and the Jebel Akhdar is primarily *serir:* a uniform pebble-strewn plain devoid of any material which could easily be moved by the wind. In the north however, a series of low escarpments border upon shallow depressions in which fluviatile deposits have accumulated to produce a poor but vitally important soil. This soil is very resistant to wind action as long as it remains undisturbed, but once the surface has been broken by the impress of the feet of sheep and camels during the winter grazing season, vast quantities of dust are exposed to become ready prey to the next strong wind. It was most likely dust produced in this fashion that contributed to the streeting observed by Hastings.

It is important to make this distinction between sand and dust since they give rise to very different phenomena once lifted into the atmosphere. Because of their small terminal velocities, dust particles may be carried in suspension to great heights, producing the duststorms so familiar to meteorologists at the desert-edge airfields. Sand is too heavy to be held in suspension in this way; instead it drives over the ground in a bounding motion (saltation), rarely rising more than a metre above the surface. It seems unlikely, therefore, that secondary transverse circulations above an established dune field would be visibly revealed by streeting since the constituent sand grains are found to be comparatively large, with a minimum grain diameter of about 0·15 mm in the finest material at the dune crests. Mobile sand grains would remain close to a sand dune surface, whereas a dust surface could give rise to dust in suspension with visible streeting.

Our understanding of the complex interrelationship between wind and sand movement depends very heavily upon theory, and particularly upon R. A. Bagnold's laboratory studies and limited field observations of more than 30 years ago.[2] Bagnold has stressed the need for more meteorological observations from the desert interiors. A full knowledge of the airflow above longitudinal dune systems must await the availability of such regular observations.

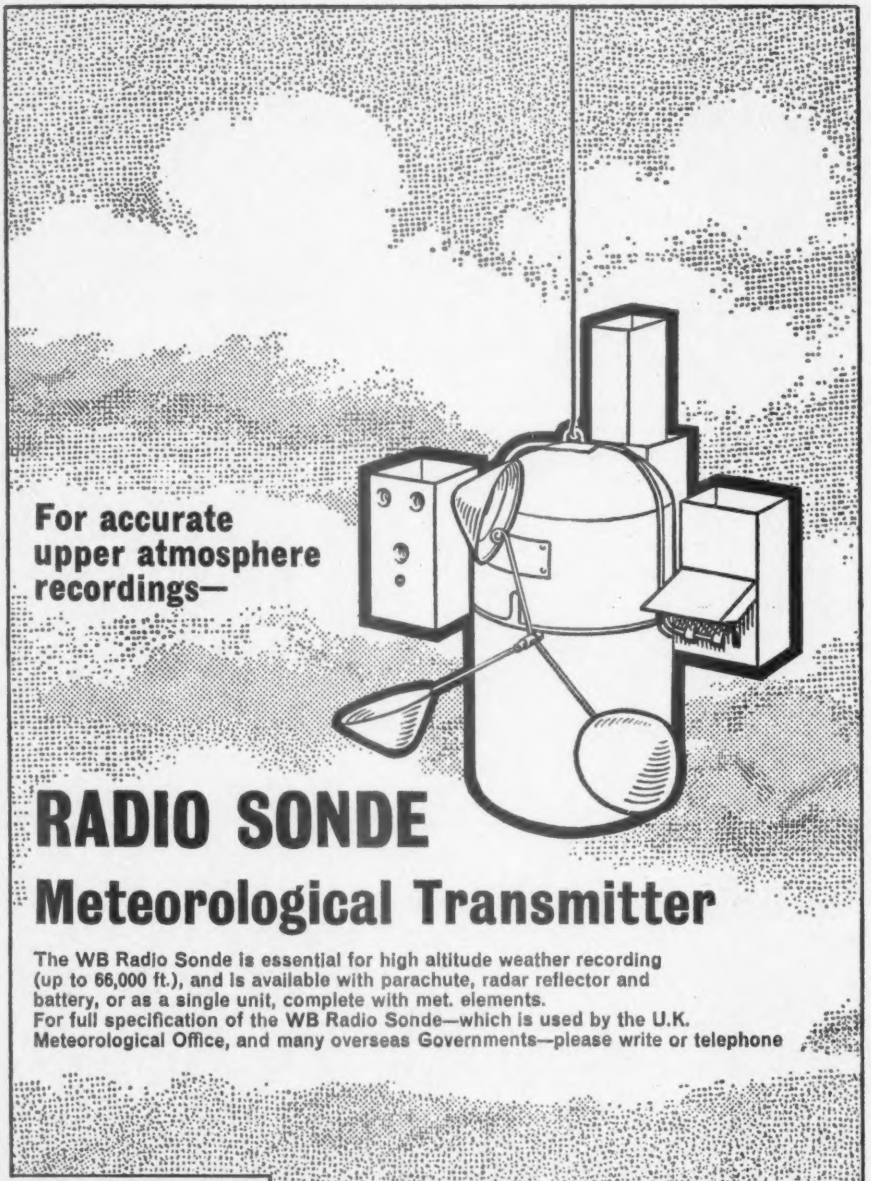
Meteorological Office,
London/Heathrow Airport W. J. T. NORRIS

REFERENCES

1. HASTINGS, J. D.; Sand streets. *Met Mag, London,* **100**, 1971, pp. 155–159.
2. BAGNOLD, R. A.; The physics of blown sand and desert dunes. London, Methuen and Co., 1941.

Meteorological Magazine: price increase

As from this month, the price of an issue of the Meteorological Magazine will be 21p and the annual subscription will be £2·82, including postage.


For accurate
upper atmosphere
recordings—
RADIO SONDE
Meteorological Transmitter
The WB Radio Sonde is essential for high altitude weather recording (up to 66,000 ft.), and is available with parachute, radar reflector and battery, or as a single unit, complete with met. elements.
For full specification of the WB Radio Sonde—which is used by the U.K. Meteorological Office, and many overseas Governments—please write or telephone
WHITELEY
ELECTRICAL RADIO CO. LTD.
MANSFIELD
NOTTS
ENGLAND
Tel: Mansfield 24762
WB187

THE METEOROLOGICAL MAGAZINE

VOL. 101 NO. 1194 JANUARY 1972

CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked "for Meteorological Magazine."

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

All inquiries relating to the insertion of advertisements in the Meteorological Magazine should be addressed to the Director of Publications, H.M. Stationery Office, Atlantic House, Holborn Viaduct, London EC1P 1BN (Telephone: 01-248 9876, extn 6075).

The Government accepts no responsibility for any of the statements in the advertisements appearing in this publication, and the inclusion of any particular advertisement is no guarantee that the goods advertised therein have received official approval.

Printed in England by The Bourne Press, Bournemouth, Hants

and published by

HER MAJESTY'S STATIONERY OFFICE

21p monthly **Annual subcription £2.82 including postage**

Dd. 500918 K16 1/72 SBN 11 400195 2